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Crop production throughout the world is dependent on soil water availability either directly through precipitation captured in the soil profile or indirectly as soil water recharge applied via irrigation. Increasing water use efficiency (WUE) is critical to ensuring that we continue to produce the food, feed, fuel, and fiber needed to sustain the world's increasing populations. Optimizing the factors that affect WUE will enhance the stability of crop production across a range of climates; however, the ever-increasing problem of climatic change increases the urgency with which we should view this issue and begin to understand the implications of the interactions between soil management factors and WUE. The increasing variability in both temperature and precipitation throughout the world raises the question of how to enhance WUE under current cropping systems. This goal has to be coupled with the sobering fact that the soils of the world continue to be degraded, and many of the critical properties that are linked to WUE of cropping systems are being negatively impacted. Increasing our ability to efficiently increase food and feed production given changes in climate and soil will require that we better understand the interactions between the soil and crop production. Wallace (2000) summarized the need to increase WUE by more effectively using water resources for plant production. The challenge for us and future generations will be to provide a stable and secure food supply and the efficient use of our natural resources—soil, water, and air.

Hatfield et al. (2001) reviewed the literature on WUE and soil management to highlight many of the options for increasing WUE through improvements in soil management. Among these options were soil management practices that affected water availability and nutrient management practices that increased the nutrient availability to the crop. They summarized the potential impacts as a relationship shown in Fig. 10–1. Soil management practices related to nutrients or water availability could change the WUE by ± 15 to 25% compared to the baseline. These changes in WUE offer potential for how we can cope with changing climate and will be explored in the remainder of this chapter. It is important to begin this discussion by first defining WUE and the principal variables that affect WUE. There have been several different forms of relationship used to characterize WUE, and these have been summarized by Tanner and Sinclair (1983). Water use efficiency is described in mathematical form as

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$$\mathrm{WUE} = Y/\mathrm{ET} \qquad [1]$$

where Y is the harvestable yield of the crop, either biomass or grain, and ET the combination of evaporation of water from the soil surface and plant leaves and transpiration through the stomates to the atmosphere. deWit (1958) first proposed this relationship after he observed there was a linear relationship between plant yield and transpiration in crop production regions with high solar radiation (e.g., the western United States) and described this relationship as

$$Y/T = m/T_{\max} \qquad [2]$$

where Y is total dry matter production, T is transpiration, m is an empirical coefficient, and $T_{\max}$ is daily free water evaporation, generally obtained from evaporation pans. Water use from the crop (ET in Eq. [1]) generally is based on total water use (ET) from the crop surface and includes evaporation from soil and plant components because of the difficulty in separating evaporation (E) from transpiration (T). Although there has been substantial progress in being able to separate E from T, this remains a challenge for most experiments; thus, the more common ET term is used.

Soil management impacts on WUE will occur through factors that affect the availability of soil water to influence ET in Eq. [1] or factors that affect Y that are not directly related to water but affect plant growth. Soil management practices can affect WUE through their direct effect on the surface energy balance:

$$\mathrm{ET} = R_n - G - H - P \qquad [3]$$

where R_n is net radiation, G is soil heat flux, H is sensible heat flux, and P is photosynthetic flux. These terms are often expressed in a variety of different units (W m^{-2}, KJ m^{-2} s^{-1}). Changes in the energy exchanges (R_n, G, and H) and the plant photosynthetic (P) efficiency are the mechanisms by which WUE is changed because these components affect the soil water balance within and among growing seasons. The methods by which soil management practices modify the energy balance components and affect WUE will provide linkages among soil management practices and WUE discussed in this chapter.

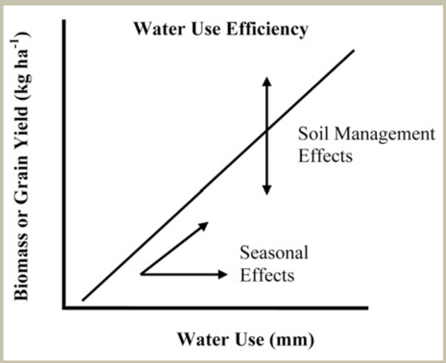

Fig. 10|1. Potential changes in water use efficiency as affected by seasonal and physical changes in soil and nutrient management (adapted from Hatfield et al., 2001).

Soil Management Practices

Modification of the Soil Surface

Soil management practices that influence WUE include manipulation of the soil surface, either by tillage system, residue management, or living mulches. The effectiveness of these practices in changing WUE varies among practices, climates, and cropping systems. All components—R_n, G, H, and P—of the energy balance (Eq. [3]) are affected by soil surface modifications. Water use efficiency has often been a concept that has been applied to either semiarid regions, where water is limited, or irrigated systems, where enhanced water management returns large dividends because of the positive impact of additional water on crop production. These areas are also those that may be the most affected by climate change impacts on precipitation patterns and amounts. Hatfield et al. (2001) summarized the range of WUE in different systems and provided an overview of the differences among soil management systems. Wallace (2000) described WUE of a crop as

$$\mathrm{WUE} = \frac{e_w}{\left(1 + \dfrac{L + E_s + R + D}{E_t}\right)} \qquad [4]$$

where e_w is the ratio of carbon fixed per unit water transpired, L is the loss of irrigation water in storage and conveyance, E_s is the evaporation from the soil surface, R is the runoff, D is the drainage from the soil profile, and E_t is the transpiration from the crop. It is easy to see how the various factors that affect water impact WUE are linked to soil management practices.

Tillage

Tillage creates changes in the soil surface that breaks apart the surface soil layer, including soil crusts, which in turn leads to an initial increase in the rate of water infiltration into the soil and ultimately increases soil water storage. Disturbing the soil surface can also cause increased soil water evaporation compared to residue-covered surfaces or undisturbed surfaces because of the exposure of moist soil to the atmosphere. Lascano and Hatfield (1992) showed that soil water evaporation occurred from the soil surface until a very thin crust of dry soil was formed and eliminated the pathway for water exchange to the atmosphere. Conversely, removing the crust will increase evaporation. Burns et al. (1971) and Papendick et al. (1973) demonstrated that disturbing the soil surface with tillage increased soil water evaporation rates compared to untilled areas. Ritchie (1971) observed that soil water evaporation affected two surface features, surface soil water content and the amount of plant cover over the soil surface. Tillage moves moist soil up to the surface where drying losses are increased. Total soil water evaporation fluxes ranged from 10 to 12 mm for a three-day period following each cultivation operation in the spring in Iowa, while evaporation fluxes from no-till fields were less than 2 mm during this same time period were less than 2 mm (Hatfield and Prueger, unpublished data, 1999). Soil water availability in the seed zone could be reduced by as much as 20 to 30 mm with aggressive field cultivation operations in the spring. To replace this soil water lost from the seed zone it is necessary to have timely precipitation events to ensure germination and emergence of the crop. In semiarid areas, soil profile water contents that are near field capacity at the onset of the growing season are critical to crop production.

Water dynamics in soils are affected by tillage. In soils with no surface residue tillage has been found to increase the saturated hydraulic conductivity (i.e., the rate of water movement when the soil is saturated), while soil water content before tillage had no measureable effect (Cresswell et al., 1993). Tillage sequence affected unsaturated hydraulic conductivity (i.e., the rate of water movement at water contents that are less than field capacity), and excessive tillage created the lowest unsaturated hydraulic conductivities through the formation of more air-filled pores. Tillage is considered to have a positive impact on water infiltration, but excessive tillage may reduce infiltration because of the direct effect on hydraulic conductivity. Christensen et al. (1994) observed that soil water was conserved during fallow periods with no-tillage compared to clean-till, and his findings were opposite of those found by Cresswell et al. (1993). They found sorghum [*Sorghum bicolor* (L.) Moench] grain yields to be increased with adoption of no-tillage because water was conserved during the fallow periods accompanied with a deeper wetting of the soil profile in no-tillage systems.

There is not a strong relationship between tillage systems and WUE because it is not possible to discuss the tillage practices without considering the effect of mulch or crop residue management since residue management is closely linked with tillage practices. Pikul and Aase (1995) observed that infiltration rates were increased because residue protected the soil surface from the direct impact raindrop energy, which caused the infiltration rate over 3 h to be 52 mm under conventional tillage in a wheat fallow and 69 mm in the annual cropping system with no-tillage when these systems were compared in the northern Great Plains. Maintaining surface cover in no-tillage systems was advantageous compared to tillage systems because of the reduced soil crusting and erosion. Decreasing tillage intensity improved soil water availability because of reduced evaporation losses, which created a trend toward improved WUE (Aase and Pikul, 1995). Good and Smika (1978) found improved water storage with chemical fallow in wheat systems. In China, He et al. (2008) found that growing wheat (*Triticum aestivum* L.) on raised beds increased WUE under irrigation compared to the traditional tillage or zero-tillage because of the increased soil water and increased soil temperature in the root zone. They also found a reduced bulk density in the upper 30 cm of the soil profile in the raised beds of their study. They concluded that manipulation of the surface to create these raised beds increased the efficiency of irrigation water use in arid areas with limited irrigation water availability.

Water storage and evaporation losses are changed through tillage practices, but equally important is the maintenance of the soil profile. Tanaka (1990) observed soil loss in the northern Great Plains decreased WUE and dry matter production and noted that preservation of topsoil depth should be a priority outcome of soil management practices. The role of tillage on efficient water use and crop growth cannot be underestimated, and evaluation of tillage systems according to their impact on WUE provides a basis for being able to directly compare management systems.

Crop Residue Management

Soil Water Availability

Changes in WUE are a direct result of covering the soil surface with residue or mulch (Johnson and Davis, 1971). Modification of soil water evaporation by the addition of residues or mulches occurs through the reduction of soil temperature, impeding water vapor diffusion, absorption of water vapor onto mulch tissue, and decreasing the windspeed gradient at the soil surface–atmosphere interface (Greb, 1966). Sauer et al. (1996a) observed that surface residue decreased soil water evaporation by 34 to 50% and creating a 15-cm bare strip with tillage increased soil water evaporation only 7% compared to weathered residue cover. Deibert et al. (1986) stated that proper soil management could lead to both increases in precipitation storage efficiency and WUE; however, tillage effects on storage efficiency were minimal in their studies. They observed in the northern Great Plains that precipitation storage efficiency was similar among continuous wheat tillage systems but exhibited the largest variation among years and locations during the non-growing season. They defined precipitation storage efficiency as the soil water stored in the upper 1.2 m relative to the non-growing season precipitation. Differences among tillage systems were 56% with no-tillage and 47% with spring-sweep operations at Williston, ND, with no differences, from 59% with no-tillage compared to 57% with spring-sweep, at Minot, ND. Variation among years was more noticeable for the tillage practices, and they found precipitation storage efficiencies ranged from 20 to 98%. This variation in storage efficiency was attributed to a combination of variation in annual precipitation and precipitation patterns. Yields under no-tillage were lower and were attributed to increased weed competition, foliar disease, and insect damage compared to spring-sweep or spring-plow operations, which resulted in a lower WUE with no-tillage (Deibert et al., 1986). In the Canadian prairies of British Columbia, Azooz and Arshad (1995) measured higher soil water contents under no-tillage plots compared to moldboard plow. Another study in eastern Canada, Ontario, found the corn (*Zea mays* L.) residue on the soil surface of no-tillage systems intercepted significant amounts of precipitation and reduced soil water evaporation (Zhai et al., 1990). An increase in available soil water in the upper meter of the soil profile was found in no-tillage versus other tillage practices in Wisconsin (Johnson et al., 1984). Reducing the tillage intensity in the upper Midwest and Canada generally increases soil water content. Reduction of tillage creates the potential for increased soil water content in the upper soil profile by increasing the physical barrier to soil water evaporation and reducing the disturbance of the soil surface that results in increased soil water evaporation.

In northern Great Plains cropping systems effective management of snow can have a significant impact on the soil water balance. Standing residue or stubble increases snow trapping and has been found to increase soil water content by 10 to 30 mm in spring (Aase and Siddoway, 1990). The effectiveness of standing residue vs. bare soil in increasing the soil water content was more evident with snow events than rainfall events. Energy exchange rates between the soil surface and the atmosphere affected by crop residue on the surface are albedo changes, altered aerodynamic coefficients, and diminished water vapor exchange rates (Eq. [3]). Sauer et al. (1996b) found the aerodynamic properties of corn stubble to change over the winter with roughness lengths and drag coefficients to be highest in the fall and lower in the spring because the residue had weathered and compacted beneath the snow layer. Increasing the roughness lengths and drag coefficients in the fall caused the water vapor exchange rates to increase. However, fresh residue on the soil surface in the fall has a larger amount of air-filled pore space, which offsets the increase caused by the altered aerodynamic properties. The addition of fresh residue on the soil surface creates the potential for rapid water loss, and the rate of water vapor movement through the stubble was the limiting factor. By the spring when the residue no long had snow cover, the aerodynamic properties were changed and the roughness lengths and drag coefficients were representative of a smoother surface and were the limiting factors to water vapor exchange.

Understanding the seasonality of changes in the aerodynamic properties of residue along with the properties of crop residue need to be evaluated to fully quantify how crop residue management can be altered to affect water management and potential water savings. Using wheat to protect young cotton (*Gossypium hirsutum* L.) plants from blowing sand in the southern High Plains offers the potential for effective management of soil water and decreasing the risk of blowing sand harming the plants. There was no observed difference in total seasonal evapotranspiration between conventional tillage practice (305 mm) and cotton planted into wheat residue with the growth terminated before maturity (304 mm) (Lascano et al., 1994). Wheat residue modified the microclimate by altering the partitioning of ET into the evaporation and transpiration components, increasing transpiration to 69% of the total ET compared to 50% for the conventional tillage practice. However, placing cotton into the wheat residue did not change cotton WUE. Hatfield (1990) observed that water vapor content increased and windspeed decreased within wheat residue, which resulted in a reduction of the water vapor gradient in wheat residue compared to bare soil. Increasing the water vapor content around the young cotton plants and decreasing the windspeed increased WUE in the early season by 25%, but this effect did not persist throughout the season because as the cotton grew above the wheat residue the effect of residue on water vapor and windspeed was no longer evident. Increasing the humidity and decreasing the windspeed around the young cotton seedling reduced the evaporation gradient, which in turn created a favorable microclimate for the cotton plant. Observations from these types of studies show the potential for modifying WUE in cropping systems by altering residue management.

Sauer et al. (1998) observed large differences in the evaporation fluxes among days because the wetness of the corn residue layer had a large effect on the partitioning of available energy into evaporation and sensible heat. On radiation limited days (i.e., overcast), with a dry soil surface, the partitioning of net radiation into evaporation was observed to be between 50 and 75%, while on sunny days evaporation was less than 20% of the net radiation. On days when the soil surface was wet, there was no observable difference in partitioning of net radiation into evaporation fluxes (Sauer et al., 1998). An interesting observation in this study was the magnitude of the changes in the radiation components because albedo changed with age of the residue and the transmissivity of radiation through the residue increased with weathering (Sauer et al., 1997). Transmissivity of radiation is a measure of energy penetration onto the soil surface and is a function of the residue area index (the amount of residue covering the soil expressed as depth of residue, similar to leaf area index). Spatial variation of crop residue across a field is extremely dynamic because the wind rearranges the residue after harvest and before decomposition commences, which in turn affects the rate of decomposition. Changing the energy balance and the partitioning into evaporation by crop residue will affect the temporal and spatial dynamics of water storage and evaporation rates throughout the year and across a field or landscape.

Soil Temperature

Residue management affects soil temperatures, and soils with surface residue are generally cooler than tilled soils (Allmaras et al., 1964; Anderson and Russell, 1964; Greb, 1966). Cooler temperatures may cause slower early season crop growth and are the primary reason given to explain limited adoption of no-tillage in the upper Midwest. Observations by Hammel (1989) in northern Idaho revealed that reduced tillage and no-tillage increased soil impedance, and when combined with the increased cool, wet soil conditions in the spring, resulted in reduced root function and diminished crop growth potential. There is a tradeoff—the addition of crop residue on the surface can increase the soil water storage, but if there is a negative impact on crop growth caused by cooler temperatures, then there is little benefit from the additional soil water on WUE.

A solution to the negative impact of crop residue can be achieved by removing the corn residue from the seedbed; when this was done Kaspar et al. (1990) observed an increased rate of corn emergence caused by higher maximum soil temperatures in the seed zone, which affect germination and emergence. There is a difference among seasons on the effect of crop residue on soil temperatures. Hatfield and Prueger (1996) observed the greatest effect on soil temperature was in the fall when the residue was fresh compared to in the spring when the residue was weathered and minimal differences were observed. There is an additional complicating factor caused by the type of soil and its inherent thermal properties. In a Monona silt loam (fine-loamy, mixed, mesic, Typic Hapludoll) there was a 1 to 2°C cooler temperature than in a Nicollet loam (fine-loamy, mixed, mesic Aquic Hapludoll) caused by thermal conductivity differences and the effect of soil water on thermal properties even when the same amount of residue was added to both soils (Sauer et al., 1996a).

In a warmer climate, the High Plains of Texas, Unger (1988) observed that soil surface temperatures were affected more by season than by residue management practices. During the summer, the highest soil temperatures were found under the standing residue of dryland wheat, while during the winter, a no-tillage treatment with shredded residue had the highest temperatures. The effect of crop residue on soil temperatures is caused by changes in the soil water content and the interactions of water with soil thermal properties, and these interacting factors must be considered in evaluating the effectiveness of residue management.

Crop Growth and Yields

Increased soil water availability from the adoption of no-till systems or increasing or maintaining crop residue can have a positive effect on crop growth and yield. Adoption of no-till in western Kansas for wheat–row crop–fallow rotations increased corn yields by 31% (Norwood, 1999). The row crops in this study included corn, sorghum, sunflower (*Helianthus annuus* L.), and soybean [*Glycine max* (L.) Merr.], and the effect was not consistent among row crops—corn yields were increased in 3 years, sunflower and sorghum in 2 years, and soybean in only 1 year. In more arid climates conservation tillage has been coupled with irrigation. Unger (1994) found increased soil water use with conservation tillage, but these practices did not enhance grain yield of either wheat or grain sorghum. Sorghum is very efficient at using precipitation during the growing season; however, Jones and Popham (1997) did not find that continuous sorghum grain yields were improved by residue management compared to fallow systems on the southern High Plains. Unger (1991) found WUE varied among years, and for eight cultivars the highest yields were from cultivars with the highest water use amounts during the season.

An opposite result was found in Australia, where Gibson et al. (1992) observed that keeping sorghum stubble on the soil surface increased sorghum yield by 393 kg ha^{-1} because of increased WUE from the greater amount of water stored in and available to be used by the crop when extracted from the soil profile compared to conventional tillage. In this study, they found that decreasing tillage frequency increased soil water extraction, but no-tillage did not result in the optimum yield or WUE (Gibson et al., 1992). Water use efficiency can be enhanced by additional availability of soil water, and in the southern High Plains, the addition of soil water through irrigation increased WUE for wheat to 8 kg ha^{-1} mm^{-1} compared to 4 kg ha^{-1} mm^{-1} under dryland conditions (Musick et al., 1994). Increasing the soil water availability leads to increased WUE when there are no other limitations to crop yield. No standard set of recommendations exists on the effectiveness of different practices for WUE because the variation among years limits our ability to quantify the exact WUE response under a suite of management practices.

Additional management factors affect WUE. For example, in Saskatchewan Tompkins et al. (1991) observed that no-tillage winter wheat yields increased with seeding rate and decreased row spacing. Decreasing the row spacing from 36 to 9 cm and increasing the seeding rate from 35 to 140 kg ha^{-1} enhanced WUE. Using these changes in management caused grain yield to increase from 1.49 to 1.68 kg m^{-2} and WUE to increase from 9.4 to 10.3 kg ha^{-1} mm^{-1}. Although total water use increased with narrow row spacing and higher plant populations, the increased yield contributed the most to increased WUE (Tompkins et al., 1991). These results have been observed in other environments. For wheat in India, WUE was optimized at the 75 kg ha^{-1} seeding rate (Srivastava and Sidique, 1978). Jones and Johnson (1991) found for grain sorghum that WUE was not affected by plant density within the row but decreased with narrow rows in 1 out of 3 years. Variation in WUE among years attributable to the row width and plant density was 75%.

There are differences among crop response to tillage and residue management. Azooz and Arshad (1998) found barley (*Hordeum vulgare* L.) and canola (*Brassica campestris* L.) to vary among years. Comparing barley and canola water use and yield in no-tillage and a 75-mm strip till with conventional tillage in a silt loam and a sandy loam soil they found an increase in yield with no-tillage and strip till in dry years, but in wet years the highest yields were from the conventional tillage system. In the dry year, WUE was increased in barley by 21% with no-tillage and 18% with strip till in the silt loam soil and in the sandy loam, 19% with no-tillage and 10% with modified no-tillage compared to conventional tillage (Azooz and Arshad, 1998). Water use efficiency was highest with conventional tillage in the wet years in this study. There have been extensive studies on WUE response to crop management. For example, Liang et al. (1991) showed higher plant populations and higher fertilizer rates coupled with increased temperatures (heat units) and water inputs during the corn growing season increased yield and WUE. The implication from this study was that early season crop growth affected WUE because of the positive effects of increased heat units and water use on early season corn growth. A similar response for wheat was measured in the Mediterranean, where WUE was increased by agronomic factors that created high yields (Zhang and Qweis, 1999).

Differences in WUE are often observed among growing seasons. Chan and Heenan (1996) measured the water use in wheat–lupin (*Trifolium subterraneum* L.) rotation and observed that differences in crop water use among years were caused by early season growth of the wheat crop because the greater the early season growth, the greater the ability of the wheat crop to extract soil water. Lupin growth did not respond to differences in soil water among years. There are interactions between wheat growth and tillage practices; however, Dao and Nguyen (1989) concluded that in spite of these it was not necessary or feasible to develop cultivars for specific tillage methods. In their study at El Reno, OK, they found that no-tillage management under unfavorable growing conditions showed the greatest response in wheat growth and yield.

Evaluation of the impacts of soil management practices on WUE does not always yield definitive answers, and there is often variation among seasons that is not completely understood. In a study of WUE in sugarbeet (*Beta vulgaris* L.) and corn, Eck and Winter (1992) evaluated how modifying the soil profile affected water use and found that although water was extracted from deeper depths of the modified soil profile, this additional water did not lead to a consistent increase in yield. Water use efficiency was affected in only one year of the study, and Eck and Winter (1992) surmised that soil profile modification did not cause a consistent benefit because of the limited impact on yield. There is large variation among years on observed values for WUE, and when digitaria (*Digitaria eriantha* spp. *Eriantha*) was compared to lucerne (*Medicago sativa* L.) under sodic soils in New South Wales, WUE varied by 110% in the digitaria, 84% in the lucerne, and 72% for the mixture (Tow, 1993).

There were no observable differences among corn hybrids, and WUE values for grain yield and biomass were the same for short season and full season hybrids (Howell et al., 1998). There were; however, differences in the seasonal patterns of soil water extraction with hybrid maturity. There are also differences among soil types on water use patterns and corn yield (Tolk et al., 1998).

Soil Nutrient Status

The impacts of nutrients on WUE were first described by Viets (1962) when he observed a positive impact on WUE from the direct effect of nutrients on improving plant growth and yield. There have been some recent suggestions by Davis and Quick (1998) that cultivar selection for improved WUE could be based on quantifying the role of nutrient management on photosynthetic rate, yield, rooting characteristics, and transpiration. Optimization of WUE could be an outcome of enhanced cultivar selection and nutrient management practices (Davis and Quick, 1998). As a positive expression of these interactions, Payne (1997) reported a combination of N management, and increased plant population enhanced WUE of pearl millet [*Pennisetum glaucum* (L.) R. Br.] grown in the Sahel. The overall suggestion is that improved nutrient balance of the crop increases crop yields and should translate to improved WUE. A conclusion from these experimental results is that WUE improvements would be derived from a more in-depth knowledge of how nutrient management influences crop growth. Although there are some general conclusions, the current literature is not consistent in documenting the relationships between nutrient management and WUE. The following examples for specific nutrients provide evidence of nutrient management impacts on crop growth and yield and the potential WUE linkage.

Nitrogen

Soil type, tillage, N source (e.g., fertilizer, manure), crop rotation, and precipitation all affect N availability to a crop. Oberle and Keeney (1990) observed that for rainfed environments, preplant and early season precipitation amounts were important factors in explaining yield responses and were the factors that caused optimal N rates for maximum corn yield. In this study, N management caused variation in yield with no difference in amounts of water use. There are major differences among locations in N response. For example, in Alabama, Reeves et al. (1993) found maximum corn yields were obtained with N additions from 93 to 134 kg ha^{-1} in a legume-based conservation system, while in Minnesota, Jokela and Randall (1989) observed that grain and total dry matter yield of corn increased N additions up to 225 kg ha^{-1}. In both studies, large differences were observed across the 3 yr of the study, and delayed N application did not influence dry matter or grain yield. Responses found for corn are different than those in wheat. Applying N at anthesis increased N use efficiency from 55 to 80% compared to N use efficiencies between 30 and 55% for preplant applications (Wuest and Cassman, 1992). Nitrogen management in wheat influences yield and grain quality, and protein content as a metric for grain quality is a critical parameter. Thus, the linkages between water and N will have to be addressed as components of the management system (Fowler et al., 1990). The findings of Jeuffroy and Bouchard (1999) demonstrated that N management in wheat influences grain number, and since grain number is a critical yield component, management practices need to be implemented that ensure the maximum number of grains per unit area are produced to obtain maximum yield. Improvements in wheat WUE can be made through N management because of its direct relationship to yield components like grain number per unit land area and grain size. Abbate et al. (1995) observed that N deficiency in wheat at anthesis affects grain number, and the number of grains per head is a function of the N content of the spikes. Strategies for improved N management to influence crop yield should consider the implications for WUE.

In addition to differences in soil and crop response, landscape position also affects N dynamics and availability to the crop. Across the landscape there are confounding interactions between water and N, Wood et al. (1991) showed slope position had little effect on plant N uptake or soil N dynamics, but aboveground biomass and plant residue production increased due to increased soil water availability from the top to the bottom of the landscape. Maskina et al. (1993) found that growth and N uptake by corn increased as residue amounts from previous crop production increased. This affect was more critical than tillage. Improvements in water availability and N increase the crop growth and potentially increase the amount of residue returned to the soil, and ultimately to the soil carbon (Halvorson et al., 1999). Increasing the cropping intensity in dryland regions, as suggested by Farahani et al. (1998), requires changes to N management practices since dryland soils have low N mineralization potential (Halvorson and Reule, 1994). The linkage between N management and water use rates is especially evident in dryland cropping systems. Changes in crop residue management used to increase WUE will have to be linked with N dynamics in the soil and across landscapes to achieve the maximum benefit of changing management practices.

There are direct effects on WUE from the addition of N fertilizer and incorporation of hairy vetch (*Vicia villosa* Roth.) residue into the soil (Corak et al., 1991). Increases in WUE from 6.1 to 8.5 kg ha^{-1} mm^{-1} in 1986 and from 9.1 to 16.6 kg ha^{-1} mm^{-1} in 1987 were found with the addition of 255 kg ha^{-1} N, with large variations between the 2 yr. Adding hairy vetch residue to the soil diminished the N fertilizer effect on WUE. There have been some general positive responses reported for N fertilizer effects on WUE for various crops, and these were attributed to the positive effect of increased biomass on WUE. Increases were found in grain sorghum (Varvel, 1995), native grasses (Smika et al., 1965), wheat (Campbell et al., 1992), and corn (Varvel,1994).

Additional soil factors that link N management and WUE have been identified in poorly drained soils. In perennial ryegrass (*Lolium perenne* L.), Stout and Schnabel (1997) found that WUE decreased with poor drainage because denitrification reduced the available N, causing reduced plant growth. They observed reductions in WUE of 26% in the spring and 20% in the summer from the decrease in biomass production. There was an increase in WUE from 2.2 to 7.7 kg ha^{-1} mm^{-1} as N application increased from 0 to 126 kg ha^{-1} for these studies. There are differences in WUE among species, including observed values for orchardgrass (*Dactylis glomerta* L.) of 20.2 kg ha^{-1} mm^{-1} and 22.7 kg ha^{-1} mm^{-1} for tall fescue (*Festuca arundinacea* Schreb.) (Stout, 1992).

Phosphorus

The information on N effects on WUE is fairly abundant, but knowledge of the effect of phosphorus is much more limited.. Water use efficiency increased from 8.5 kg ha^{-1} mm^{-1} at 0 kg ha^{-1} of P to 12.2 kg ha^{-1} mm^{-1} at 100 kg ha^{-1} of P for chickpea (*Cicer arietinum* L.) because of the effect of additional P on improved yield, water use, and WUE (Singh and Bhushan, 1980). Improvements in WUE were due to increased soil water depletion with addition of P fertilizer and the accompanying increase in chickpea yield.

The effect of adding P is more pronounced in low-phosphorus soils; for example, addition of P fertilizer was found to increase both dry matter yield and WUE in pearl millet (Payne et al., 1992, 1995). Enhanced dry matter production in crops relative to water use rates and amounts from improved soil nutrient status will directly increase WUE.

Climate Change Impacts

There are differences in WUE among climates which are caused by the variations in the water use rate among crops. Zhang et al. (2000) observed that water use and WUE for chickpea and lentil (*Lens culinaris* Medikus) in northern Syria was dependent on the rainfall amounts and the patterns during the growing season. They found that yields increased during the wet seasons of this 12-season study and when supplemental irrigation was applied. The WUE for grain production was 3.8 kg ha^{-1} mm^{-1} for lentil and 3.2 kg ha^{-1} mm^{-1} for chickpea. They found that in the Mediterranean climate the lentil was better adapted to this climate. Sadras and Angus (2006) compared WUE for wheat in four environments, southeastern Australia, North American Great Plains, China Loess Plateau, and the Mediterranean Basin. In their study they compiled data from published studies from these sites and computed WUE. Based on this analysis the average WUE (kg ha^{-1} mm^{-1}) for grain production was 5.3 for the south-central Great Plains of North America, 7.6 for the Mediterranean Basin, 8.9 for the northern Great Plains of North America, 9.8 for the China Loess Plateau, and 9.9 for southeastern Australia. They observed that the variation in WUE was related to evapotranspiration around the time of flowering. The variation in yield was due to water availability during the critical time of flowering. Variation in rainfall among seasons was the primary factor creating differences in wheat yield and WUE.

Climate change impacts on agriculture have been compiled by Hatfield et al. (2008) in a summary of the potential effects on climatic factors, temperature, CO_2, and precipitation on crop growth and yield. Climate scenarios for the future were developed by Tebaldi et al. (2006) in which temperature and precipitation patterns across the United States for the next 50 yr show a warming trend for most of the United States of 1.5 to 2°C and a slight increase in precipitation over most of the United States. They also projected an increase in warm nights, defined as occurring when the minimum temperature is above the 90th percentile of the climatological distribution for the day. These changes are typical of other regions of the world and will impact WUE in several ways. The increase in temperature will increase the ET of the crop and increase the potential for water stress, thus lowering biomass and grain yield production. This will ultimately reduce the transpiration amounts and decrease production and lower WUE. Seasons with greater rainfall will benefit because of the potential positive impact on crop growth and development and increased WUE. These projected results are similar to the multisite comparison made by Sadras and Angus (2006), in which environments with seasonal water deficits at critical times would have reduced WUE. The increase in the nighttime temperatures and the negative impact on biomass and grain yield would reduce the WUE because the increased respiration at night would offset any gains during the day, and although soil management practices would increase the water availability to the crop, there may not be a positive gain from the increased water. Further analysis is required to determine the role that soil management could play in offsetting these impacts.

Increasing CO_2 has been linked with increasing WUE. Morison (1987) showed that for both C_3 and C_4 species, stomatal conductance was reduced about 40% with a doubling of CO_2, thereby increasing water conservation and reducing plant water deficits. A 12% reduction in seasonal transpiration and 51% increase in WUE was found for soybean crops in sunlit, controlled-environment chambers grown at ambient and doubled CO_2 (Jones et al., 1985). Doubling of CO_2 decreased transpiration in wheat by 8% (Andre and du Cloux, 1993). Also using environment chambers, Reddy et al. (2000) found transpiration was reduced by 8% in cotton canopies when CO_2 was doubled. Using lysimeters in Arizona for cotton experiments, Kimball and Idso (1983) found a 4% reduction in seasonal water use of cotton at ambient versus 650 ppm CO_2. Reductions in ET reduction caused by increased CO_2 in soybean, ranged from 9 to 16% among seasons when grown at 550 compared to 375 ppm in Free-Air Carbon Exchange (FACE) experiments in Illinois (Bernacchi et al., 2007). There is an interaction of changing CO_2 and temperature on soybean ET, and Allen et al. (2003) detected a 9% reduction with doubling of CO_2 in sunlit, controlled-environment chambers for a 28/18°C treatment, but no reduction in ET when the plants were grown at 40/30°C. The conclusion is that the effect of CO_2 on reducing ET is temperature dependent and would also vary with species because of the variation in temperature responses among plants. A similar response was found by Horie et al. (2000) for rice, when a doubling of CO_2 caused a 15% reduction in ET at 26°C, but increased ET at 29.5°C. With doubled CO_2 and rice grown at 24 to 26°C, WUE increased by 50%, but as the temperature increased, the CO_2 enrichment effect diminished.

Interactions of CO_2 enrichment with climatic factors of water supply and evaporative demand are especially evident under water deficit conditions (Boote et al., 1997). Reductions in stomatal conductance with elevated CO_2 will potentially lead to improved soil water conservation and reduced plant water stress, especially for crops grown with periodic soil water deficit or under high evaporative demand. The changes in CO_2 will enhance the differences that have been reported by Sadras and Angus (2006) and increase the need for soil management practices that conserve soil water.

Climate changes in precipitation patterns will affect the amount and distribution of rainfall. These changes will render the impact of soil management practices even more important in the future. Stability of crop production will require the maintenance of crop yields and soil water availability will be one of the primary factors affecting WUE.

Challenges

Development of soil management practices that enhance WUE given the changes in climate over the next 50 years revolve around optimization of the availability of soil water to the crop. Even though increases in CO_2

have demonstrated their positive impact on plant growth and water use efficiency, these effects would be negated when soil water is limited due to lack of precipitation. Although there can be less positive impact on WUE from soil management practices when temperatures increase, there are still positive changes that can be made in WUE through improved nutrient management to enhance plant growth.

A challenge for the research community and producers will be to understand the interactions among the soil management factors, plant growth and yield, and the changing climate. There can be positive increases in WUE with improved management, as shown in Fig. 10|1. However, the response of these changes when plant growth is altered with the changed climate needs to be incorporated into our understanding. The challenge will be to extend these findings into areas where the research data are limited to be able to help producers understand the changes they can institute in their management decisions that will optimize WUE. Increasing WUE through management will help ensure a more stable food supply for future generations.

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